CENTER FOR TRANSPORTATION INFRASTRUCTURE AND SAFETY

Adding Faculty in Transportation Areas: Research Progress on Geomaterials and Non-Destructive Sensor Technology

by

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16. Abstract

This funding was provided to help departments build up their faculty in the transportation field over the next years. Broad areas will be considered as listed in the UTC mission or other areas that relate to State Departments of Transportation and MoDOT in particular as stated in their goals, interests, and objectives. Dr. Bate was supported by NUTC Faculty Support Funds from 2011 to 2014. During this period, he continued his research from his Ph.D. study and extended into several new directions, including bender element S-wave sensor development, high volume reuse of fly ash in geotechnical engineering, and curing process monitoring of self-consolidating concrete, and made significant progresses. Five journal papers and five conference papers were published. As a final report, the abstract of the publications are attached.

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Adding Faculty in Transportation Areas

Research Progress on Geomaterials and Non-Destructive Sensor Technology

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Dr. Bate was supported by NUTC Faculty Support Funds from 2011 to 2014. During this period, he continued his research from his Ph.D. study and extended into several new directions, including bender element S-wave sensor development, high volume reuse of fly ash in geotechnical engineering, and curing process monitoring of self-consolidating concrete, and made significant progresses. Five journal papers and five conference papers were published. As a final report, the abstract of the publications are attached.

Kang, X., Kang, G.-C., and **Bate, B.** (2014). Shear Wave Velocity Anisotropy of Kaolinite Using a Floating Wall Consolidometer-Type Bender Element Testing System. *Geotechnical Testing Journal*. 37(5): 1-15.

A new floating wall consolidometer-type bender element testing system was developed to study the stiffness anisotropy of clays at applied vertical stresses up to 800 kPa. One-dimensional slurry-consolidated Georgia RP-2 kaolinite samples, prepared with 0.005 and 1 mol/l NaCl solutions, were tested in this system. A floating wall design eliminated the detrimental bending moment that acts upon the horizontally installed benders as a result of soil settlement in a traditional fixed wall setup, which significantly improved the signal quality and bender reuse. Floating wall–soil interface resistance was quantified with pulling tests. Analytical equations were then derived to calculate the wall resistance-corrected vertical effective stress. As a result, stresses applied to the soil were more accurately determined. The bender element (BE) test was used to measure kaolinite's shear wave velocity (Vs), thereby quantifying the small strain stiffness of soils. Average Vs results for RP-2 kaolinite were lower than those for other kaolinites reported in the literature. This was postulated to be primarily due to the longer and more tortuous chains of particle contacts associated with the smaller median diameter (d50 1/4 0.36 lm) of RP-2 kaolinite samples. BE test results indicated that Vs increased with stress, density, and concentration. The hierarchy of Vs in three orthogonal directions (i.e., hh > hv > vh) agreed with results in the literature. It was also illustrated that Vs anisotropy increased with applied stress and decreased during unloading. In addition, a comparison was made between the BE test in the new floating wall consolidometer and the BE test in a triaxial testing setup.

Bate, B. and Burns, S.E. (2014). Complex Dielectric Permittivity of Organically Modified Bentonite Suspensions (0.2 - 1.3 GHz), *Canadian Geotechnical Journal.* 51: 782-794.

To quantify the impact of organic carbon on the complex dielectric permittivity of organoclays, nine organically modified clays were synthesized with controlled organic carbon structure and density of loading. Resonance polarization responses were observed for six of the organoclays at resonant frequencies from 0.74 to 1.37 GHz; however, organoclays synthesized with the smallest organic cations did not exhibit resonant frequency. A structural model of water molecules near the surface of organoclay and in the diffuse layer was proposed, which consists of a surface-bound water layer, an organic cation- interactive zone, and bulk water. The Cole–Cole equation was used to fit the resonance response. Increasing the density of loading (30% to 100% of the cation exchange capacity of the base clay) on the clay surface led to a reduction in the resonance time of the clay, while increasing the size of the organic cation led to a longer dielectric resonance time for the clay, which indicates that altering the structure and density of the organic carbon phase changed the degree of constraint of water molecules within the clay's interlayer. However, the impact of organic carbon content on real permittivity was not significant. Water content had no obvious effect on the resonant frequency of the organoclays at high water content (porosity ranging from 0.7 to 1.0) in this study. In addition, it was shown that a linear approximation was sufficient in relating real permittivity of organoclay suspensions to porosity, and the effective conductivity decreased linearly proportional to porosity. That is, the real permittivity and effective conductivity were dominated by that of the aqueous phase until the inception of resonance polarization.

Bate, B., Zhao, Q., and Burns, S.E. (2014). Impact of Organic Coatings on the Frictional Strength of Organically Modified Clay. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*. 140(1): 228-236.

Organic matter is frequently encountered in both naturally occurring and engineered particulate media. Charged functional groups in the organic matter can lead to cation exchange within the clay interlayer, which results in the formation of an organic coating on the clay surfaces and alters the interfacial frictional regime in the soil mass. This study investigated the triaxial shear frictional behavior of montmorillonite particles coated with a controlled organic phase composed of quaternary ammonium cations. Through cation exchange, organic cations were loaded onto the clay's interlayer exchange sites, with control on the density of organic coverage and structure of the organic cation. Results demonstrated that increasing the total organic carbon content of the clay resulted in increasing frictional resistance regardless of whether the increase in carbon content was attributable to increased density of organic loading, increased cation size, or increased cation tail length. Concentrating organic carbon in one of the quaternary ammonium cation branch positions led to measureable gains in strength compared with distributing the carbon over all four branch positions. Measured critical-state friction angles for the organoclays ranged between 34 and 61_, whereas all tested organoclays demonstrated peak strength coupled with contractive tendencies. The presence of the organic cations in the clay interlayer led to alteration of the structure within the interlayer and is believed to have combined with forces from electrostatic bonding between the organic cation head groups and the clay surface, as well as chain entanglement and dewatering, to contribute to the increased frictional resistance of the modified organoclays.

Bate, B., Choo, H.W., and Burns, S.E. (2013). Dynamic Properties of Fine-Grained Soils Engineered with a Controlled Organic Phase. *Soil Dynamics and Earthquake Engineering*. 53: 176-186.

Soils with high organic content are frequently encountered beneath earthquake sensitive infrastructure, such as bridges or levees. Historically, the dynamic properties of these organically rich soils have been difficult to predict due to the heterogeneity of the natural organic matter that is found in natural soils, even though their response to dynamic loading remains critical to assessing the ongoing stability of the infrastructure. In this study, an experimental investigation was performed on a montmorillonite soil that was modified with a controlled organic phase. Quaternary ammonium cations were exchanged onto the soil particle surfaces through cation exchange with the clay′s naturally occurring cations (e.g., Na+, Ca2+). Quaternary ammonium cations with a variable structure were chosen, which allowed control on the cation′s size and length of alkyl chain, as well as a control on the density of organic loading on the clay surface. The dynamic properties of organoclays were then quantified experimentally using resonant column and bender element tests. This study demonstrated that the increase in the total organic carbon content of the soil increased the shear wave velocity and stiffness of the soil (Gmax) due to a reduction in the void ratio of the organically rich soil. Cation structure did have a measureable impact on the soil stiffness, with organic cations with carbon concentrated primarily in a single tail demonstrating higher stiffness than those soils engineered with a branched cation structure. When compared to inorganic soils, the presence of the organic cations in the soil increased the range of linear elastic behavior of that soil, with the organoclays having a threshold strain of 0.024% or higher. The soil samples with the largest percentage of total organic carbon and the lowest void ratio demonstrated the largest damping ratio (ratio between dissipated and stored energy) during cyclic loading at small strain. Regression analysis of the dynamic test results demonstrated that the total organic content and the void ratio were the most dominant factors in determining Gmax for the high organic content clays.

Bate, B. and Zhang, L.M. (2013). Use of Vacuum for the Stabilization of Dry Sand Slopes. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*. 139(1): 143-151.

Vacuum is proposed as a means for rescuing soil slopes showing signs of impending failure. Two aspects associated with the pro- posed method were studied; namely, the theory of airflow through dry soils and the effectiveness of vacuum for enhancing the stability of soil slopes. A model test device was developed, and two series of tests were carried out using this device. One was a series of tests on pore-air pressure distributions in dry sand slopes, and the second series involved dry sand slope stability tests. The results revealed that a vacuum (negative pore-air pressure) even as small as 20.4 kPa significantly increased the stability of the model slopes with dimensions of 0.9 3 0.5 3 0.28 m (length 3 width 3 height). The pore-air pressure distributions in the model slopes were simulated using a finite-element partial differential equation solver, FlexPDE. Fick's law and mass conservation were used to formulate the airflow through dry soils. Good agreement was achieved between the experiment results and the numerical simulations. A computer routine, called Slope-Air, was developed for slope stability analysis using Bishop's simplified method and considering the pore-air pressure distributions in the slope. The calculated factors of safety of the model slopes at failure were consistent with the results of the model slope stability tests.

Kang, X., **Bate, B.**, and Ge, L. (2014). Shear Wave Velocity and Its Anisotropy of Granular Materials of Different Sizes. Geo-Congress 2014, Atlanta, GA, United States. GSP 234: 2029-2041.

Small strain stiffness of granular materials is of importance to many engineering applications, such as earthquake engineering, pavement, machine foundation, embankment subjected to tidal impacts, and foundations for structures under wind loads. Shear wave velocity, which is an indicator of the stiffness, was measured with a newly developed bender element testing system. Test data supported that this testing system is effective in evaluating the shear wave velocity and its anisotropy of uniform spherical granular materials, including glass beads, uniform medium and fine sands. Influencing factors on the *Vs* such as grain size and applied stress were studied. Two components of the soil stiffness anisotropy, namely stress anisotropy and fabric anisotropy were discussed. It was found that *Vs* anisotropy emerged for fine-grained soils at high consolidation stresses, indicating that the contact normal, or the magnitude and direction of interparticle contacts, between particles could be anisotropic. *Vs* anisotropy is not obvious for 6mm glass bead samples. An empirical equation relating α and β coefficient of equation $V_s = \alpha(\frac{\sigma'_m}{1kPa})^\beta$ was proposed based on test results in this study: $\beta = \frac{1217.93}{(\alpha + 117.21)^{1.64}}$. It was also observed that given other conditions equal, large particles, which possess significant less number of contacts than small particles do, seem to transmit shear waves faster. However, the similar *Vs* values of granular samples with intermediate d50 sizes (0.26 – 3 mm) indicated that other mechanism(s) would contribute to the recorded *Vs* values.

Kang, X., Zhao, X., and **Bate, B.** (2013). Microscopic and Physicochemical Studies of Fly Ash-Kaolinite Suspensions. International Workshop in Experimental Micromechanics for Geomaterials. May 23-24, 2013. The University of Hong Kong.

The sedimentation behavior of fine grained soil is largely dependent on its pore fluid chemistry. Physicochemical properties of the pore fluid, such as ionic strength and pH, could greatly influence the micro structure of kaolinite which in turn influences the sedimentation behavior. Other than ionic effect, adding fly ash can also cause different sedimentation behaviors due to the change of gradation, increased ionic strength and pozzolanic reactions. There are several tests to characterize the kaolinite micro fabric, such as sedimentation test, grain size distribution test, viscosity test, zeta potential test, and scanning electron microscopy (SEM). The objective of this research was to investigate the influence of ionic concentration and fly ash on the sedimentation behavior of kaolinite. In addition, zeta potential and particle size distribution in supernatant and suspensions were measured and analyzed. The zeta potential of kaolinite was found closely related to the particle size, micro fabric and settling speed. It was found that an increase in the percentage of fly ash in the fly ash soil mixture could cause an increase in the settling speed. The addition of fly ash was found more efficiency than the ionic concentration because the fly ash can not only interact with kaolinite particles but also increase the ionic strength in the dissolution so that the kaolinite could flocculate and aggregate which in turn increases the settling speed.

Kang, X., Zhao, X., and **Bate, B.** (2013). Sedimentation Behavior of Fly Ash-Kaolinite Mixtures, The 7th International Conference on Case Histories in Geotechnical Engineering (7ICCHGE). April 29-May 4, 2013, Chicago, IL, USA. No. 6.19b.

The sedimentation behavior of fine grained soil is largely dependent on its pore fluid chemistry. Different ionic concentration will lead to different fabrics of soil suspension, such as dispersion, aggregation, and flocculation. The ionic concentration also influences the thickness of the Diffuse Double Layer (DDL), which leads to the change in the final sediment volumes. Besides the ionic concentration influence, adding different amount of fly ash (FA) can also cause different sedimentation behaviors. The objective of this research was to quantify the interaction between fly ash and fine grained soils by comparing the influence of ionic concentration with that of fly ash on the sedimentation behavior of kaolinite. It was found that an increase in the percentage of fly ash in FA-kaolinite mixture could cause an increase in the settling speed. The final sedimentation volume decreased as the ionic concentration increased. The addition of fly ash was found more efficiency than the ionic concentration, because the fly ash could not only interact with kaolinite particles but also increase the ionic concentration in the dissolution by precipitation of Calcium hydroxide and pozzolanic reaction products.

Ge, L., Zhao, H., and **Bate, B.** (2012). Implementation of Numerical Optimization Techniques in Constitutive Model Calibration. The 2nd International Symposium on Constitutive Modeling of Geomaterials, ISMODEL 2012, October 15-16, 2012, Beijing, China.

When a conventional method such as linear regression is insufficient to identify the constants and parameters of an advanced constitutive model, numerical optimization techniques are often used. In employing numerical optimization to constitutive model calibration, an objective function essentially needs to be formulated in the form of nonlinear least squares where the sum of the differences between the measured and computed data points are quantified. When a minimum value of the objection function is obtained, the corresponding variables are the optimized model constants and parameters. Due to the complexity in the format of objective functions in constitutive model calibration, gradient-based methods are seldom used. In this paper, non-gradient based methods namely Direct algorithm was implemented to calibrate a modified Cam-Clay model against laboratory data.

Bate, B. and Burns, S.E. (2012). Influencing Factors on the Dynamic Properties of Organobentonites. Geo-Congress 2012, Oakland, CA, USA.

The dynamic responses of soils are important engineering properties, especially for soils with high organic contents, because these soils can underlay critical support structures such as highway bridges or levees. Consequently, the initial tangent shear modulus (Gmax), secant shear modulus ratio (G/Gmax), and damping ratio (D) are important parameters in evaluating the dynamic soil behavior for soils subjected to earthquake, wind, waves, traffic, and equipment vibration. In this study, these dynamic properties of organobentonites were quantified experimentally using resonant column tests. The results from this study were evaluated in terms of the effect of shear strain, organic content, and plasticity index. The organobentonites tested in this study were engineered with an organic phase that was controlled in terms of structure and density of loading. The results indicate that the total organic carbon content reduced the net surface charge on clay particle, which in turn increased the bonding between the organic cations and clay surface. The resistance is then increased, leading to increase in stiffness.